Multi-agent Based Federated Control of Large-scale Systems with Application to Ship Roll Control

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Outline

- Objective
- Introduction
- Developed research
- Simulation result
- Conclusions

Objective

Develop a federated control scheme and stability framework that connects many individual entities with simple controllers to achieve overall system performance as a group

Introduction - Large-scale Systems

Large-scale systems refer to systems that consist of several interconnected local systems

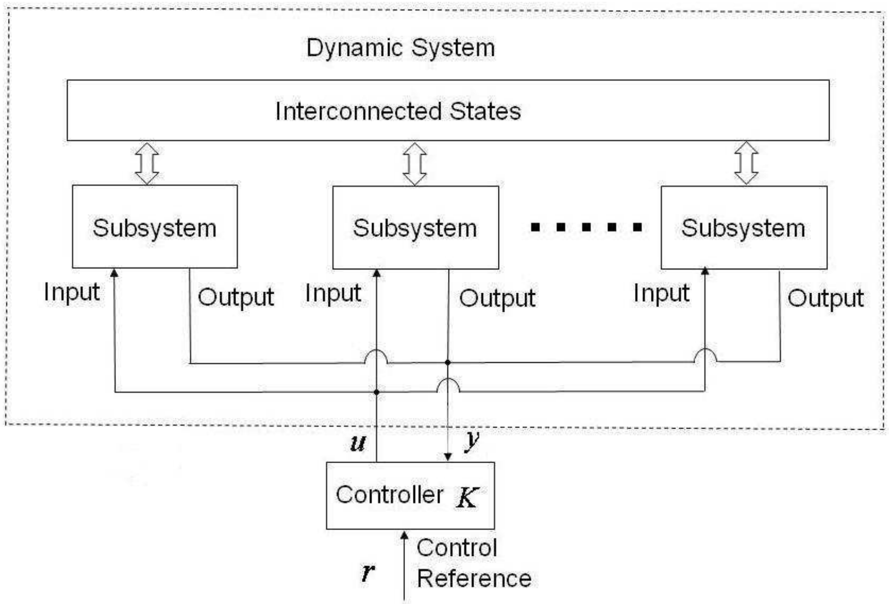
- A large scale dynamic system is characterized by these factors
  - High dimensionality of state variables
  - High complexity of computation
  - High dimensionality of input and output states
- The majority of natural processes consist of multiple sub-systems
- Most practical engineering systems consist of multiple sub-systems

Introduction -Centralized Control

- There is an enormous amount of literature on stability analysis and design of linear control systems
- The literature is insufficient in the area of stability analysis and design on federated control of large-scale systems

$$\mathbf{S}: \quad \dot{x} = Ax + Bu$$

where x is the state vector. u is the control input. A and B are the system matrices

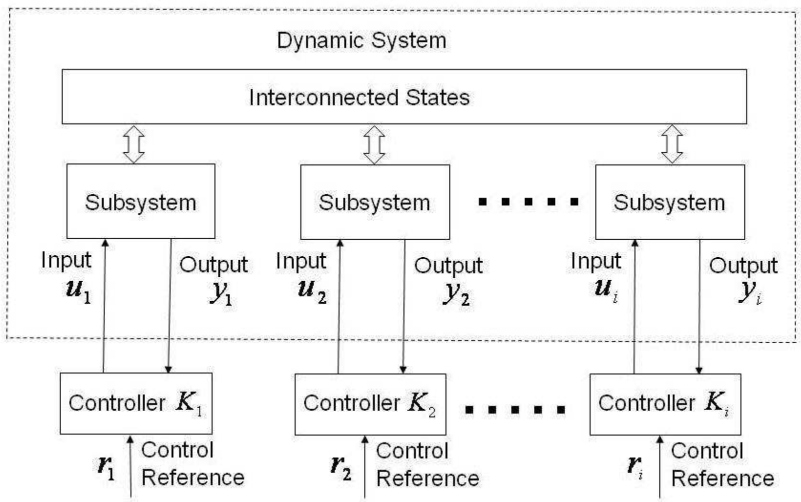


Introduction -Decentralized Control

Control of large-scale systems is often accomplished by decomposing them into many manageable small sub-systems and then applying traditional control schemes

$$\textbf{S:} \quad \dot{x}_i = \underbrace{A_i x_i + B_i u_i}_{\text{sub-systems}} + \underbrace{\sum_{j=1}^{N} e_{ij} A_{ij} x_j}_{\text{interconnected states}} \qquad i \in \{1, \cdots, N\}$$

where x_i is the i-th state vector. u_i is the i-th control input. A_i and B_i are the system matrices



Connective Stability - Decentralized Control

Consider a large-scale system

$$S\textbf{:}\quad \dot{x}_i = \underbrace{f_i(t, x_i, u_i)}_{\text{interconnected of } N \text{ subsystem}} + \underbrace{h_i(t, e_{i1}x_1, e_{i2}x_2, \cdots, e_{iN}x_N)}_{\text{interconnection functions}} \quad i \in \{1, \cdots, N\}$$

Aggregate matrix $W = (w_{ij})$ defined by

$$w_{ij} = \begin{cases} 1 - e_{ij}\kappa_i\xi_{ii}, & i = j \\ -e_{ij}\kappa_i\xi_{ij}, & i \neq j \end{cases}$$

The decentralized system **S** is connectively stable if the matrix W is a real symmetric positive definite matrix

Introduction - Multi-agent Control

- The concept of multi-agent based control came from the Artificial Intelligent research
- The multi-agent system is a networked system composed of multiple intelligent agents that are autonomous enough to operate independently
- Intelligent agents are abstractions of software entities that are autonomous, capable of sensing and directing action towards the environment, and seek to achieve goals
- The agents are usually cooperative agents that aim to achieve a common goal

Introduction - Characteristics of Multi-agent

Characteristics of multi-agent systems are:

- Each agent has incomplete information of the overall system **(Local views)**
- Each agent has limited capabilities for solving the problem **(Simple)**
- The global control is of the system usually omitted **(Decentralization)**
- Sensing and computation are distributed to each agent **(Autonomy)**
- Computation is asynchronous

Fundamental nature of the agents: autonomous, communicative and reactive

Introduction - Multi-agent Model

- Consider a group of N identical agents, moving in a R^m space maintaining a consensus via local communication with their neighbors on a graph $G = (V, E)$
- An agent could be described mathematically as a double integrator plant

$$\begin{cases} \dot{x}_i = v_i \\ \dot{v}_i = u_i \end{cases}$$

$x_i \in R^m$ is the position of the i-th agent. $v_i \in R^m$ is the velocity and $u_i \in R^m$ is the agent interconnection control associated with the i-th agent

The control objective is

- All agents move at a desired speed
- Maintaining constant distances between each agent

Introduction - Multi-agent Control

A typical example of the control law

$$u_i = \underbrace{c_1 \sum_{j \in N_i} \nabla \Psi(\|x_j - x_i\|)\eta_{ij}}_{\text{potential}} + \underbrace{c_2 \sum_{j \in N_i} a_{ij}(v_j - v_i)}_{\text{consensus}} + \underbrace{c_3(-k_p(x_i - x_r) - k_v(v_i - v_r))}_{\text{navigation}}$$

The potential function Ψ is a user defined function satisfying certain properties for a particular problem

$$\Psi(x) = \begin{cases} Ax^2 + Bx + a, & x \in [0, d] \\ \frac{b}{c}(x - r)\exp(-\frac{(x-r)^2}{c}), & x \in [d, \infty) \end{cases}$$

Stability - Multi-agent Control

Consider the Hamiltonian function $H(x,v) = \underbrace{P(x)}_{\text{collective potential}} + \underbrace{K(v)}_{\text{collective kinetic}}$

$$
\begin{aligned}
P(x) &= \sum_{i=1} \sum_{j \neq i} \Psi(\|x_j - x_i\|) \\
K(v) &= \frac{1}{2} \sum_{i=1} \| v_i \|^2
\end{aligned}
$$

Following Lyapunov stability concept, differentiating the Hamiltonian function, yields

$$
\begin{aligned}
\dot{H} &= \sum_{i=1} \langle \nabla P, \frac{dx}{dt} \rangle + \langle \frac{dv}{dt}, v \rangle \\
&= \langle \nabla P, v \rangle + \langle -\nabla P - Lv, v \rangle \\
&= -\langle Lv, v \rangle \leq 0
\end{aligned}
$$

where equality holds only when $v = 0$. L is always symmetric and positive semi-definite

The chosen Hamiltonian is stable in the sense of Lyapunov

and all agents asymptotically converge to the desired formation

Summary of Current State of the Art

- Centralized control method
  - A common approach that combines all the sub-systems into a large dimension model
- Decentralized control method
  - A frequently used technique to decompose a large-scale system into manageable small sub-systems
- Multi-agent based control
  - Modeling each sub-system as a particle

No Good Methods Exist for Large-scale Systems Considering Sub-system Dynamics

Drawbacks of Existing Approach

There is an enormous amount of literature on analysis and design of linear control systems, however it is insufficient in the area of stability analysis on federated control of large-scale systems

- Centralized Control paradigm cannot meet the challenges of global performance requirements and stability
- Traditional decentralized method can lose flexibility and scalability
- Computation is synchronized in decentralized control scheme
- Common agent based control method may be too simple to explain sub-system dynamics behavior
- Agent-based control schemes normally ignore the sub-system dynamics

Federated Control - Developed Research

Develop system stability evaluation and control methodology frameworks for large-scale systems using agent-based federated control

- The federated control concept is motivated by the political structure of a federal government
- Each entity based controller maintains its own control law for local stability
- Each entity has partial observations of the state of other entities via communication networks and executes the local control law correspondingly to satisfy the performance requirements at the overall system level

Enables cooperative management of multiple autonomous, independent and interrelated systems

Federated Control - Advantages

Federated control scheme connects many individual entities with simple controllers to achieve overall system performance as a group

- Federated control is implemented in an agent based software controller
- The concept of federated control with the incorporation of multi-agents provides the capability to revolutionize cooperative decentralized control
- Federated control enhances the overall connected system performance robustness in a cooperative and interactive fashion

Existing Examples - Federated Control

Stampede: Group of self propelled dynamics agree upon certain quantities of interest and move in the same direction

- Collective behavior
- Cooperative behavior
- Coordinative behavior

Potential Application - Federated Control

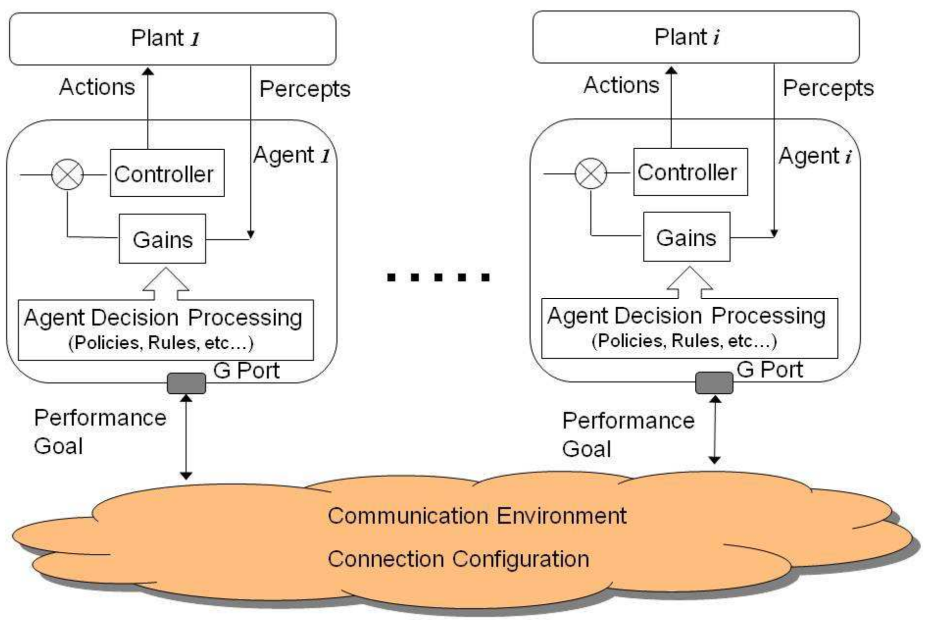
- Separation: Steer to avoid crowding and collision
- Alignment: Steer towards the average heading
- Cohesion: Steer towards a position maintaining unity

Characteristics- Federated Control

- No global system control **(Decentralization)**
- Each agent having incomplete information of the overall system **(Local views)**
- Each agent having limited capabilities for solving the problem **(Simplified controller)**
- The observation of the neighbor agent states being based on an agent's self stability **(Selfishness)**
- Each agent based controller maintaining its own control law for its local stability **(Self-sufficient)**
- Sensing and computation being distributed to each agent **(Autonomy)**
- Individual agent performance being constrained by global consensus **(Federated control)**

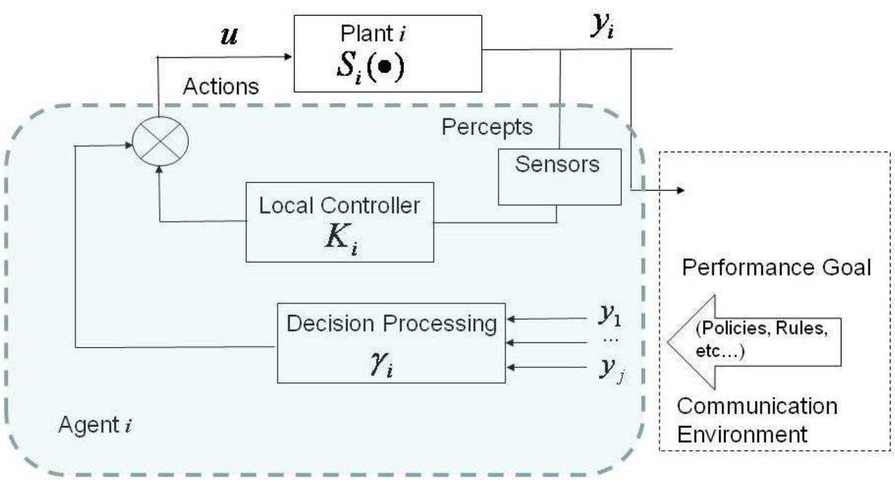
Federated Control - Architecture

- Federated control composes local autonomous entities (agent-based controllers) that cooperate to provide an overall (large-scale) system behavior
- Agent represents an independent controller of a local sub-system
- Each agent interconnects with its appropriate neighbor(s) via communication



Federated Control - Structure

- The global goal at the federal level is communicated by the agents via the communication network.
- Each agent makes its control decision independently and adjusts its controller accordingly upon receiving the goal request and the state information from the other agents at the local level
- Each agent has partial observations of the state from other agents via communication networks



Federated Control - Formulation

- A linear federated control system can be constructed as

$$\mathbf{S_i}: \quad \dot{x}_i = A_i x_i + B_i u_i \qquad i \in \{1, \cdots, N\}$$

$$y_i = C_i x_i$$

$$u_i = u_i^{LocalControl} + u_i^{AgentControl}$$

- A general form of the i-th agent controller

$$u_i^{AgentControl} = \underbrace{\gamma_3 \Psi_i(h(y_i - y_j))}_{\text{Potential term}} + \underbrace{\gamma_2(\sum_{j \in N}(y_i - y_j))}_{\text{Consensus term}} + \underbrace{\gamma_1(-k_i(x_i^{desired} - x_i))}_{\text{Federated term}}$$

Stability Analysis- Linear Interconnected System

- Linear interconnected system

$$\mathbf{S:}\quad \dot{x}_i = A_i x_i + B_i u_i^{\text{Local Control}} + \gamma_i \sum_{j=1}^{N} e_{ij} A_{ij} x_j \quad i \in \{1, \cdots, N\}$$

where e_{ij} is the interconnection matrix and γ_i is the consensus connective strength

- Stability analysis is based upon the concept of vector Lyapunov functions

$$V_i(x_i) = x_i^T H_i x_i$$

where H_i is a positive definite matrix

- The system **S** is connectively stable if the matrix W is positive definite

$$W = (w_{ij}) = \begin{cases} \frac{\lambda_{min}(G_i)}{2\lambda_{max}(H_i)} - e_{ii}\lambda_{max}^{\frac{1}{2}}(A_{ii}^T A_{ii}), & i = j \\ -e_{ij}\lambda_{max}^{\frac{1}{2}}(A_{ij}^T A_{ij}), & i \neq j \end{cases}$$

where G_i is a symmetric positive matrix and satisfies the Lyapunov matrix equation:

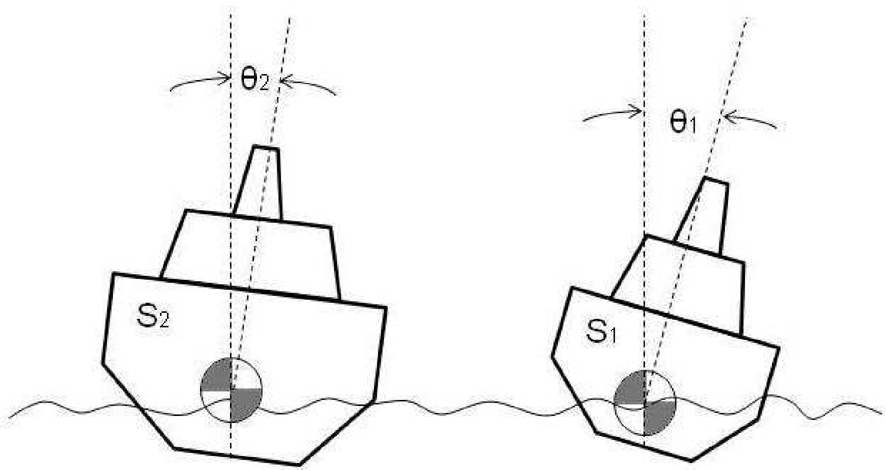
$$A_i^T H_i + H_i A_i^T + G_i = 0$$

A Typical Example - Two Ships in Roll Motion

The ship models are described as

$$\mathbf{S_1}_{\textit{open-loop}}: \quad \dot{x}_1 = \begin{bmatrix} 0 & 1 \\ -0.0288 & 0 \end{bmatrix} x_1 + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_1$$

$$\mathbf{S_2}_{\textit{open-loop}}: \quad \dot{x}_2 = \begin{bmatrix} 0 & 1 \\ -0.0029 & 0 \end{bmatrix} x_2 + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_2$$



A Typical Example - Formulation

- It is assumed that each ship observes the state of the other ship
- Each entity maintains a connection with the neighboring entity using connective strengths γ_1 and γ_2

$$\mathbf{S_1}_{\textit{closed-loop-interconnected}}: \quad \dot{x}_1 = \begin{bmatrix} 0 & 1 \\ -84.7035 & -13.4499 \end{bmatrix} x_1 + \begin{bmatrix} 0 & \gamma_1 \\ \gamma_1 & 0 \end{bmatrix} x_2$$

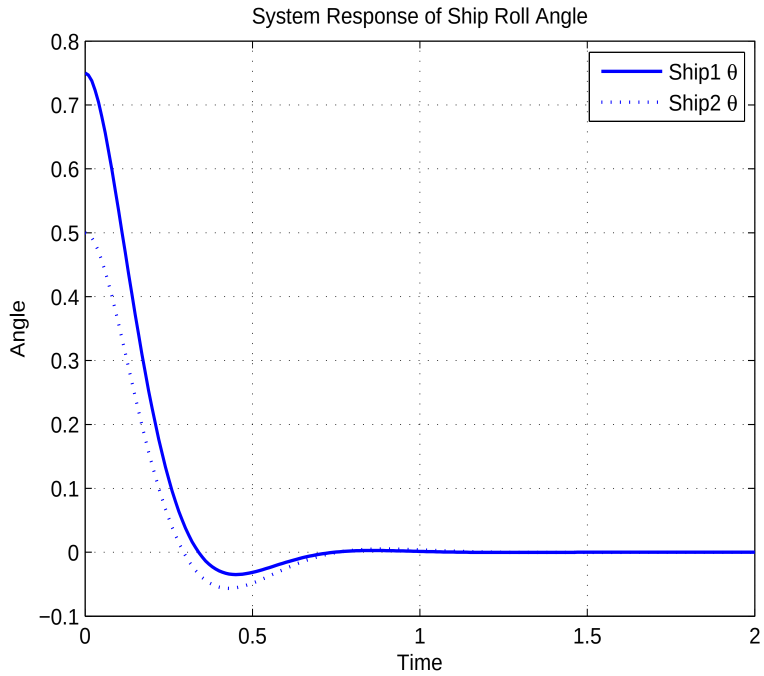
$$\mathbf{S_2}_{\textit{closed-loop-interconnected}}: \quad \dot{x}_2 = \begin{bmatrix} 0 & 1 \\ -65.5551 & -10.2131 \end{bmatrix} x_2 + \begin{bmatrix} 0 & \gamma_2 \\ \gamma_2 & 0 \end{bmatrix} x_1$$

A Typical Example - Connective Stability

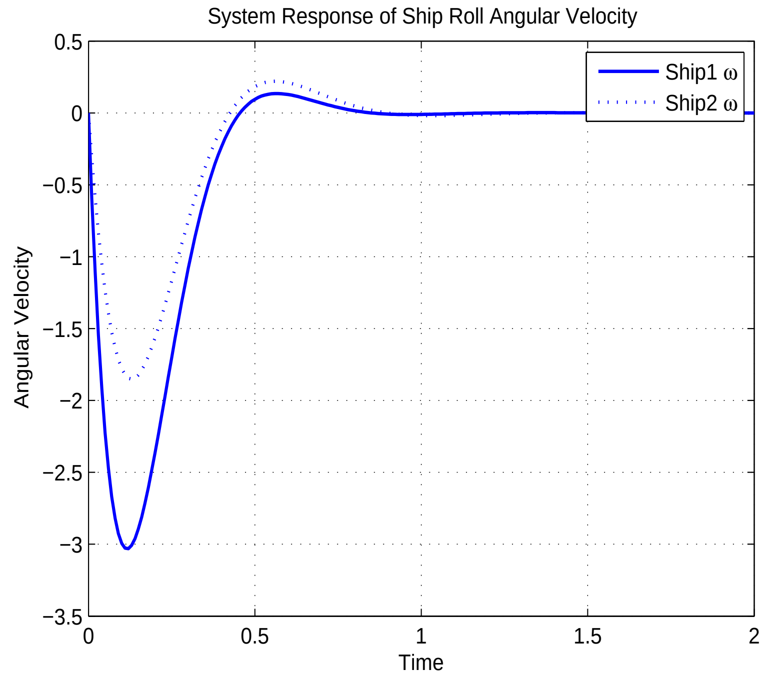
- The Lyapunov function is defined as $v(x_i) = x_i^T H x_i$
- H is a positive definite matrix
- The system S_i will be connectively stable based on the determination of $\gamma_i = max\{\frac{\lambda_{min}(G_i)}{2\lambda_{max}(H_i)}\}$, subject to the Lyapunov matrix equation $A_i^T H_i + H_i A_i^T + G_i = 0$
- It implies that the connective strengths are $\gamma_1 = 0.1531$ and $\gamma_2 = 0.1499$

A Typical Example - Simulation

Both ship's roll control agents successfully stabilize the ship roll motion when an initial disturbance is presented



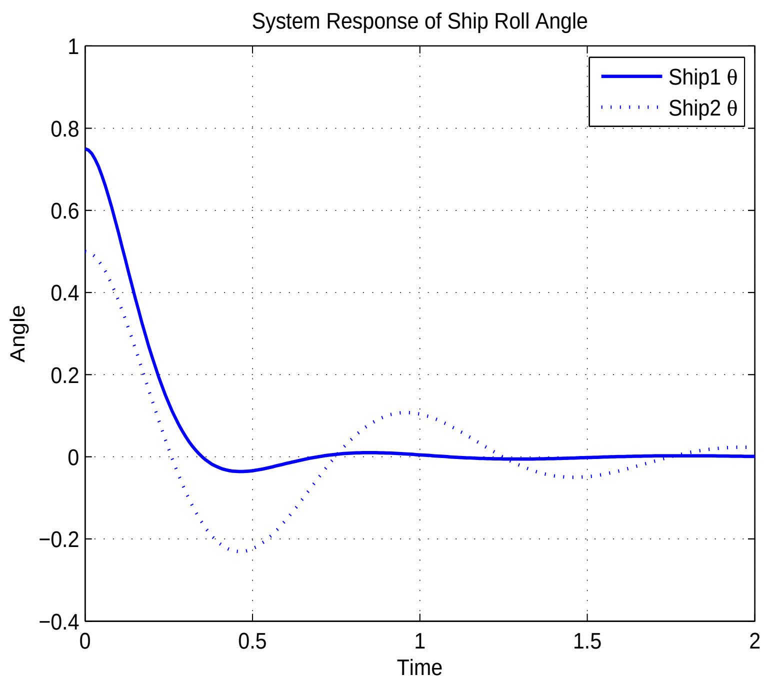
Ship Motion θ Control



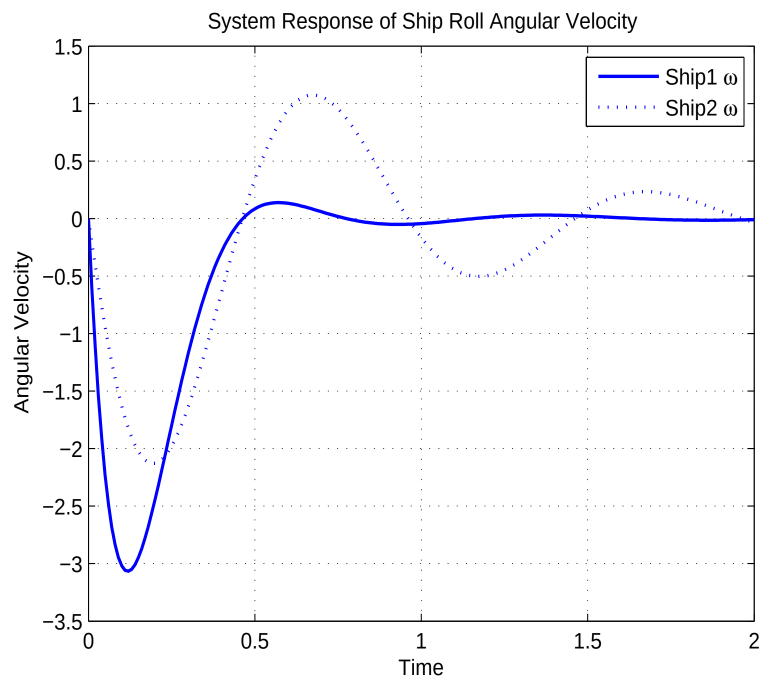
Ship Roll Motion ω Control

A Typical Example - Simulation

Because the connective strengths were properly chosen, then the ship 1 roll motion stabilizing performance was minimally impacted by the roll oscillation of ship 2



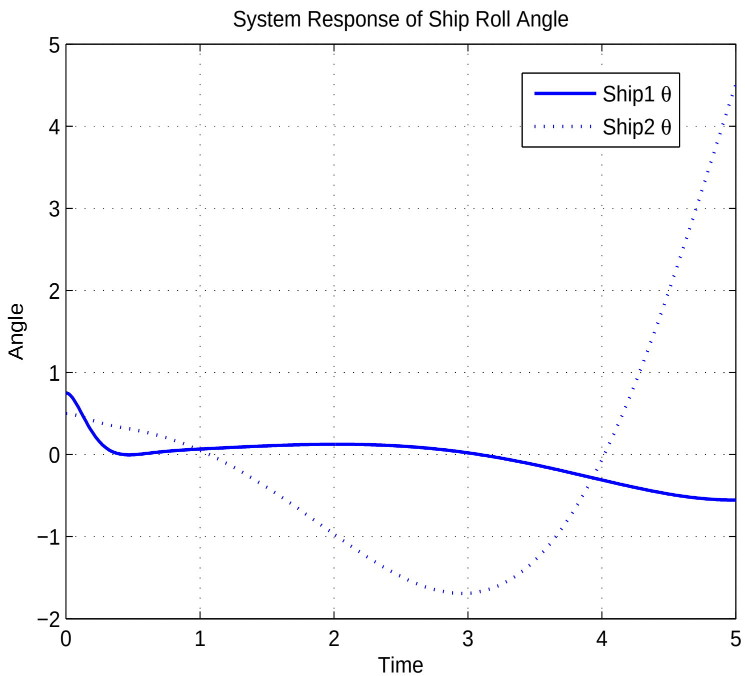
Ship Motion θ Control



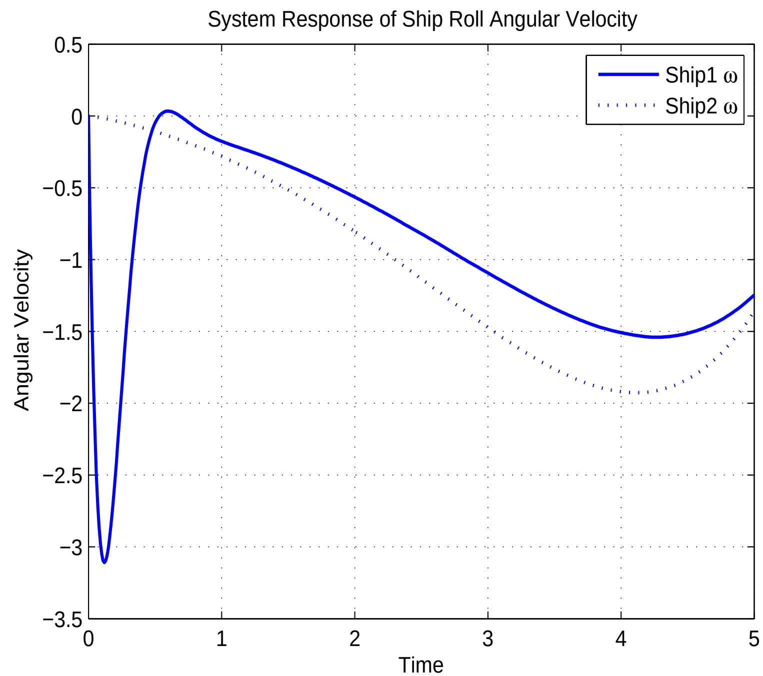
Ship Roll Motion ω Control

A Typical Example - Simulation

An unstable system would affect the stability of the neighboring system, and the stable neighboring system should reject the connectivity to the unstable neighbor to maintain its own stability



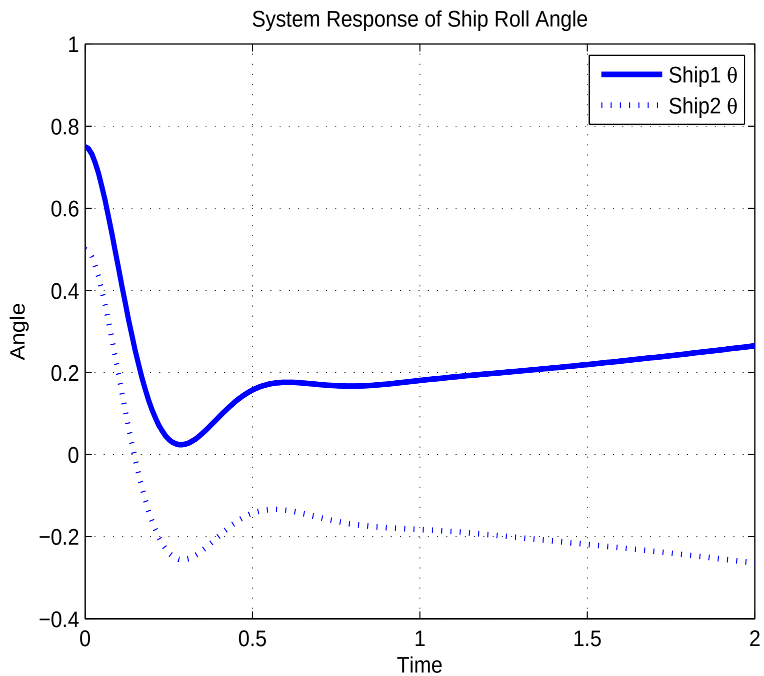
Ship Motion θ Control



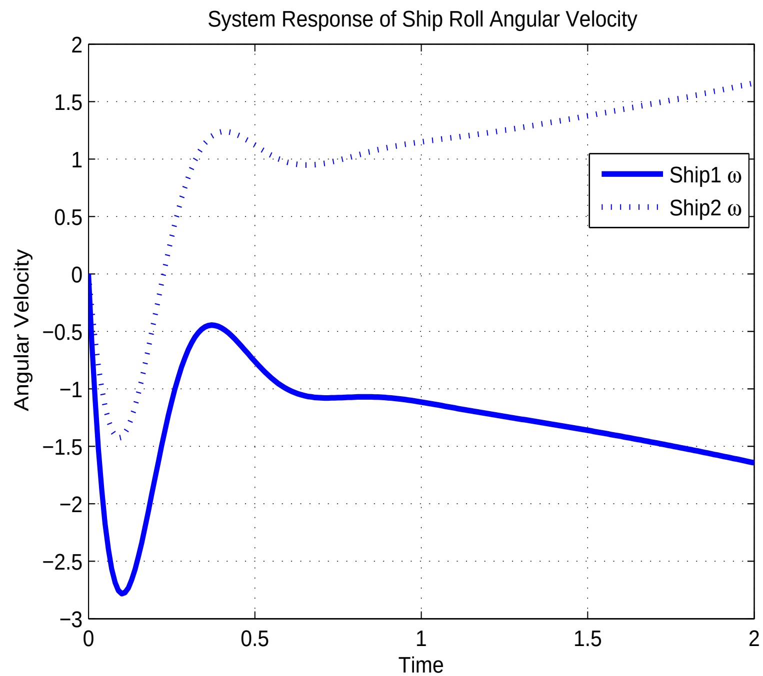
Ship Roll Motion ω Control

A Typical Example - Simulation

The connective strength is improperly computed and the two sub-systems are connected through these wrongly computed γs, then the overall connected system will be unstable



Ship Motion θ Control (Improperly Computed γ)



Ship Roll Motion ω Control (Improperly Computed γ)

Conclusions

- The concept of federated cooperative control of large-scale systems and its implementation using multi-agent based framework is presented
- The multi-agent interconnection and cooperative control ties single agents together to form a large-scale system
- Large-scale system stability through a multi-agent based controller is proved using the Lyapunov approach and computing the appropriate agent connective strength

Q and A

Thank you